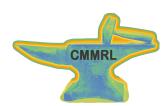
Swarm-enabled Infrastructure-Mapping for Rapid Damage Assessment Following Earthquakes

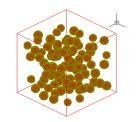
Tarek I. Zohdi

Chair, U. C. Berkeley Computational and Data Science and Engineering Program Chancellor's Professor, Department of Mechanical Engineering W. C. Hall Endowed Chair in Engineering

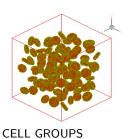
August 8, 2018



FAMILY OF COUPLED DISCONTINUOUS SYSTEMS



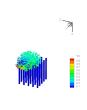
EM-COMPOSITES



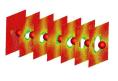
CHARGED SPRAYS



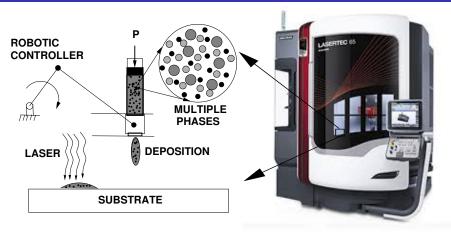
SWARMS(BBC PHOTO)



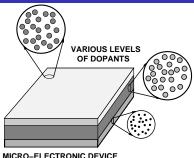
OPTICS



EM-FABRIC

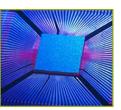


- INDUSTRIAL GOAL: RAPID SIMULTANEOUS CONTROL OF DEPOSITION, LASERS AND MATERIALS
- 3DP COMBINES: POSITIONING ↔ DEPOSITION ↔ HEATING ↔ FUNCTIONALIZED MATERIALS
- NEXT-GENERATION MACHINES: https://www.youtube.com/watch?v=g8sT8ESfjrg-NEED GUIDANCE!
- RESEARCH COLLABORATORS: AHPCRC. APPLE. ARAMCO. ARL. AUTODESK. BASF. BOEING. DOE. FAA. LAWRENCE BERKELEY, LAWRENCE LIVERMORE, LOCKHEED-MARTIN, DMG-MORI, PEER, POWLEY FOUNDATION, SAMSUNG, SANDIA, SIEMENS, TOYOTA











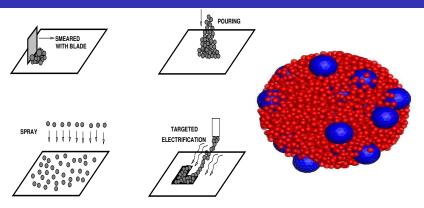






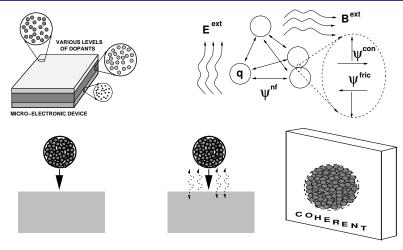
- DESIRED PROPERTIES: (1) ELASTIC (2) THERMAL (3) ELECTRICAL (4) MAGNETIC (5) OPTICAL ETC.
- KEY MOTIVATION: STRATEGIC/RARE MATERIAL REPLACEMENT WITH MICRO-DESIGNED MIXTURES
- KEY INGREDIENT: SPECIALIZED PROPERTY DESIGN-BY USE OF FINE-SCALE PARTICLES
- ULTIMATE OBJECTIVE: REDUCE PRODUCT DEVELOPMENT TIME AND COSTS THROUGH SIMULATION

PLACEMENT OF PARTICLES: MANY APPROACHES TO GET THE PARTICLES INTO THE CORRECT LOCATION



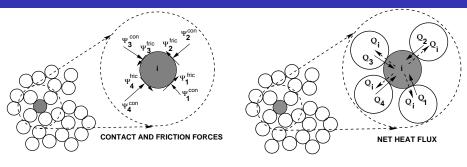
- METHOD 1: DOCTOR BLADE TO SMEAR PARTICLES-THEN HEAT/LASER (COMMON)
- METHOD 2: POUR FLUIDIZED/INK PARTICLES-THEN HEAT/LASER (COMMON)
- METHOD 3: SPRAY AEROSOLIZED/ATOMIZED PARTICLES-THEN HEAT/LASER (COMMON)
- METHOD 4: ELECTRICALLY GUIDE PARTICLES (MIXTURES)-THEN HEAT/LASER ACCURATE=FUTURE
- PROVIDES EXTREME FAULT-TOLERANCE (ROBOTIC ERROR COMPENSATION)
- ELECTRIFICATION AND CHARGING PRODUCES CONTROLLABLE FLUID-LIKE BEHAVIOR
- SECONDARY (BLUE) PARTICLES FUNCTIONALIZED THE MIXTURE FOR DESIRED PROPERTIES

: DEPOSITION PROCESSING: MODELS FOR CHARGED PARTICULATE DYNAMICS



- DYNAMICS: $m_i\ddot{r}_i = \Psi_i^{tot}(r_1,...,r_n) = \Psi_i^{nf} + \Psi_i^{con} + \Psi_i^{fric} + q_i(\boldsymbol{E}^{ext} + \boldsymbol{v}_i \times \boldsymbol{B}^{ext})$
- HEAT TRANSFER: $m_i C_i \dot{\theta}_i = CONDUCTION + IMPACT + SOURCES, ETC.$

COUPLED GOVERNING MULTIPHYSICS EQUATIONS



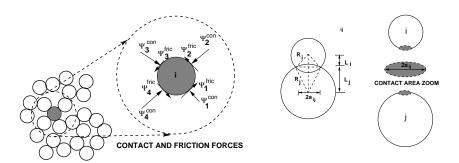
• DYNAMICS:
$$m_i\ddot{r}_i = \Psi_i^{tot}(r_1,...,r_n) = \Psi_i^{nf} + \Psi_i^{con} + \Psi_i^{fric} + q_i(E^{ext} + v_i \times B^{ext})$$

• NEAR-FIELD:
$$\Psi_i^{nf} = \sum_{j \neq i}^{n} \left(\underbrace{\left(\underbrace{\alpha_1 || \mathbf{r}_i - \mathbf{r}_j ||^{-\beta_1}}_{\text{attraction}} - \underbrace{\alpha_2 || \mathbf{r}_i - \mathbf{r}_j ||^{-\beta_2}}_{\text{repulsion}} \right) \underbrace{\mathbf{n}_{ij}}_{\text{unit vector}} \right)$$

HEAT-FLOW:

$$\int_{\omega} \rho C \frac{d\theta}{dt} \, dV = -\int_{\partial \omega} \mathbf{Q} \cdot \mathbf{n} \, dA + \int_{\omega} \mathcal{H} \, dV \Rightarrow m_i C_i \frac{d\theta_i}{dt} = \underbrace{\sum_{j=1}^{C} \mathbf{K}_{ij} \frac{\theta_j - \theta_i}{||\mathbf{r}_i - \mathbf{r}_j||} A_{ij}^c}_{Q_i} + \mathcal{H}_i$$

DETAILS-MECHANICAL PARTICLE-TO-PARTICLE CONTACT AND BONDING



- CONTACT: $\Psi_{ij}^{con} \propto -K_{\rho} |\mathcal{E}_{ij}|^{\rho\rho} n_{ij} A_{ij}^c$ where $\mathcal{E}_{ij} = \frac{||r_i r_j|| (R_i + R_j)}{(R_i + R_i)}$ and $A_{ij}^c = \pi a_{ij}^2$
- FRICTION: $\Psi_{ij}^{\mathit{fric}} = \mu_d ||\Psi_{ij}^{\mathit{con}}|| \tau_{ij}$
- ADHESION/BONDING: IF $\mathcal{E}_{ij} \leq 0$ AND $|\mathcal{E}_{ij}| \geq \mathcal{E}^*$ THEN $\Psi_{ii}^{bond} = K_b |\mathcal{E}_{ij}|^{p_b} n_{ij} A_{ii}^c$
- TOTAL FORCES: $\Psi_i^{tot} \stackrel{\text{def}}{=} \Psi_i^{con} + \Psi_i^{fric} + \Psi_i^{wall} + \Psi_i^{bond} + \Psi_i^{nf} + q_i(E^{ext} + v_i \times B^{ext})$
- CONTACT LIBRARY: HERTZ, BRADLEY, JOHNSON-KENDEL-ROBERTS, DERJAGUIN-MULLER-TOPOROV
- EMBEDDING TEMPERATURE DEPENDENCY IS CRITICAL FOR SELECTIVE LASER SINTERING/MELTING

COUPLED IMPLICIT MULTIPHYSICAL TIME-STEPPING

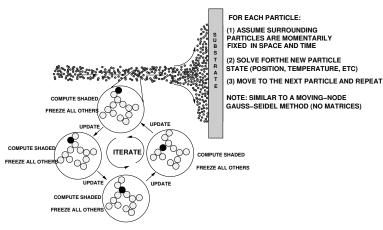
$$\begin{aligned} \text{VELOCITY}: & \pmb{v}_i(t+\Delta t) &= \pmb{v}_i(t) + \frac{1}{m_i} \left(\int_t^{t+\Delta t} \pmb{\Psi}_i^{nf} \ dt + \int_t^{t+\Delta t} \pmb{\Psi}_i^{con} \ dt + \int_t^{t+\Delta t} \pmb{\Psi}_i^{fric} \ dt + \int_t^{t+\Delta t} \pmb{\Psi}_i^{e+m} \ dt + etc \right) \\ &= \pmb{v}_i(t) + \frac{1}{m_i} \int_t^{t+\Delta t} \pmb{\Psi}_i^{tot} \ dt \\ &\approx \pmb{v}_i(t) + \frac{1}{m_i} \left(\left(\phi \pmb{\Psi}_i^{tot}(t+\Delta t) + (1-\phi) \pmb{\Psi}_i^{tot}(t) \right) \Delta t \right) \end{aligned}$$

$$\begin{aligned} &\text{POSITION}: \pmb{r}_i(t+\Delta t) &\approx \pmb{r}_i(t) + \pmb{v}_i(t) \Delta t + \frac{\phi(\Delta t)^2}{m_i} \left(\phi \pmb{\Psi}_i^{tot}(t+\Delta t) + (1-\phi) \pmb{\Psi}_i^{tot}(t) \right) \end{aligned}$$

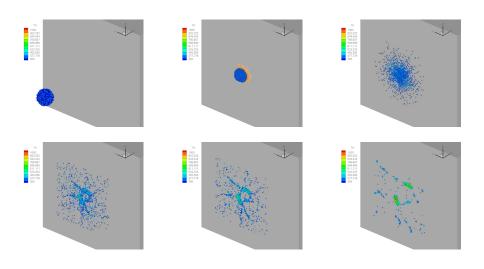
 $\approx \theta_i(t) + \frac{\Delta t}{TC} \left(\phi(\mathcal{Q}_i(t+\Delta t) + \mathcal{H}_i(t+\Delta t)) + (1-\phi)(\mathcal{Q}_i(t) + \mathcal{H}_i(t)) \right)$

ANGULAR MOMENTUM:
$$\dot{H}_{i,cm} = \frac{d(\bar{I}_i \cdot \omega_i)}{dt} = M_{i,cm}^{EXT} \Rightarrow H_{i,cm} = \bar{I}_{i,s}\omega_i = \frac{2}{5}m_iR_i^2\omega_i$$
 TIME-STEPPING: $\omega_i(t+\Delta t) = \omega_i(t) + \frac{\Delta t}{\bar{I}_{i,s}} \left(\phi M_{i,cm}^{EXT}(t+\Delta t) + (1-\phi) M_{i,cm}^{EXT}(t)\right)$ $M_{i,cm}^{EXT} = \text{FRICTIONAL INTERACTION AND ROLLING RESISTANCE}$

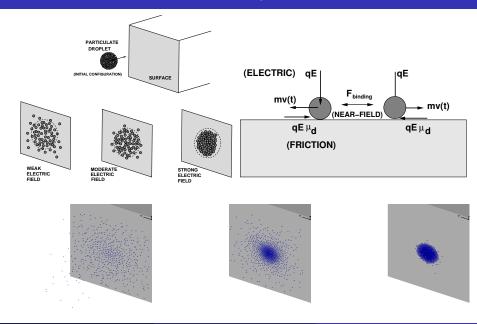
THERMAL : $\theta_i(t + \Delta t) = \theta_i(t) + \frac{1}{m \cdot C} \left(\int_{t}^{t+\Delta t} Q_i dt + \int_{t}^{t+\Delta t} \mathcal{H}_i dt \right)$



- ABSTRACT RECURSION: $\mathcal{A}(r^{l+1}) = \mathcal{F} = \mathcal{G}(r^{l+1}) r^{l+1} + \mathcal{R} = 0 \Rightarrow r^{l+1,K} = \mathcal{G}(r^{l+1,K-1}) + \mathcal{R}$
- FIXED-POINT ITERATION: $\mathbf{r}^{L+1,K} = \frac{\phi^2(\Delta t)^2}{\mathbf{v}^{tot}(\mathbf{r}^{L+1,K-1}) + \mathbf{r}^L + \mathbf{v}^L \Delta t + \frac{\phi(1-\phi)(\Delta t)^2}{\mathbf{v}^{tot}(\mathbf{r}^L)} \mathbf{v}^{tot}(\mathbf{r}^L)}$ G(rL+1,K-1)R

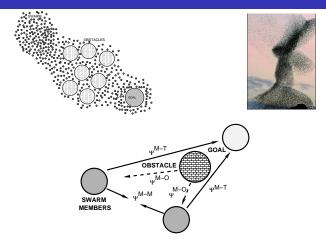


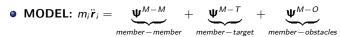
A RAPID DESIGN TOOL: EXAMPLE-ELECTRICALLY CONTROLLED/TARGETED DROPLET DEPOSITION





MODELING SWARMS: LARGE-SCALE BIOMIMICRY





GOAL: USE ANIMAL BEHAVIOR TO CREATE SYNTHETIC SWARMS

THE RISE OF QUADCOPTERS







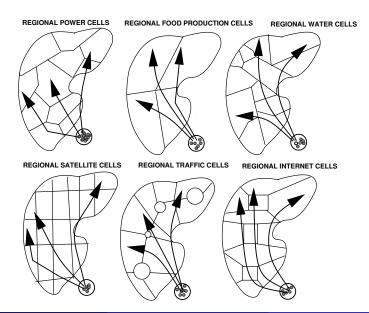




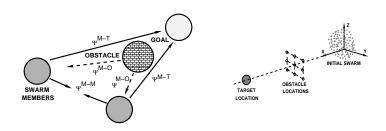








SWARM MODELING: TYPES OF INTERACTION

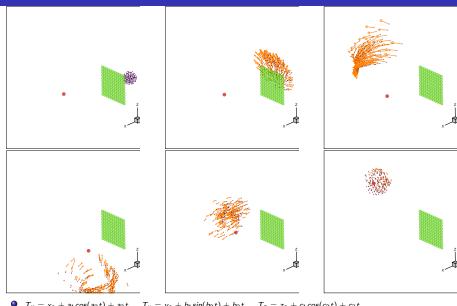


- DYNAMICS: $m_i\ddot{r}_i = \Psi(r_1, r_2, ..., r_i, ..., r_n) = \Psi_i^{M-M} + \Psi_i^{M-T} + \Psi_i^{M-O}$
- MEMBER : $\Psi_{:}^{M-M} =$

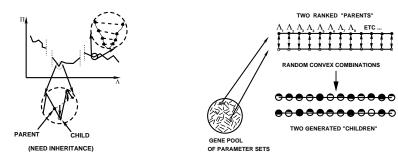
$$\sum_{k \neq i}^{n} \left(\left(\underbrace{\alpha_{1}^{M-M} || \boldsymbol{r}_{i} - \boldsymbol{r}_{k}||^{\beta_{1}^{M-M}}}_{\text{attraction}} - \underbrace{\alpha_{2}^{M-M} || \boldsymbol{r}_{i} - \boldsymbol{r}_{k}||^{-\beta_{2}^{M-M}}}_{\text{repulsion}} \right) \frac{\boldsymbol{r}_{k} - \boldsymbol{r}_{i}}{|| \boldsymbol{r}_{k} - \boldsymbol{r}_{i}||} \right)$$

- TARGET: $\mathbf{\Psi}_{i}^{M-T} = \left(\alpha^{M-T} || \mathbf{r}_{*} \mathbf{r}_{i}||^{\beta^{M-T}}\right) \frac{\mathbf{r}_{*} \mathbf{r}_{i}}{||\mathbf{r}_{*} \mathbf{r}_{i}||}$
- OBSTACLE: $\Psi_i^{M-O} = -\sum_{i=1}^{q} \left(\left(\alpha^{M-O} || \mathbf{r}_{oj} \mathbf{r}_i ||^{-\beta^{M-O}} \right) \frac{\mathbf{r}_{oj} \mathbf{r}_i}{|| \mathbf{r}_{oi} \mathbf{r}_i ||} \right)$

MODEL PROBLEM: CHASING A MOVING TARGET



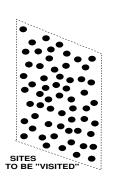
 $T_x = x_0 + a_1 \cos(a_2 t) + a_3 t, \quad T_y = y_0 + b_1 \sin(b_2 t) + b_3 t, \quad T_z = z_0 + c_1 \cos(c_2 t) + c_3 t$



- (a) a population (P) of different parameter sets are generated at random
- (b) performance of each parameter set is tested and all ranked from top to bottom
- (c) best parameter sets (parents) are mated pairwise producing two offspring
- (d) worst performing genetic strings eliminated, new strings introduced
- (e) Rescale and restart search around best design every few generations
- (f) Employ gradient-based methods afterwards in the local "valleys"
- REMARK: IDEAL FOR LARGE-SCALE PARALLEL COMPUTATION

SWARM SELF-ORGANIZATION-SEARCHING MULTIPLE SITES







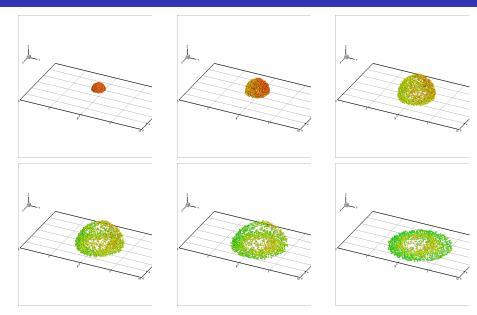
- lacktriangledown Example-design variables: interaction parameters= $lpha_i$, eta_i , $i=1,\ldots,N$
- STARLINGS (STURNUS VULGARIS): INTERACT WITH SPECIFIC MEMBERS
- ANOTHER CASE: INTERACTION WITH EVERY OTHER SWARM MEMBER
- ANOTHER CASE: INTERACTION WITHIN A COMMUNICATION RADIUS
- ANOTHER CASE: INTERACTION WITHIN A VISUAL FIELD
- THE KEY IS TO TRANSLATE BEHAVIOR INTO EQUATIONS





- DYNAMICS: $m_i \frac{d\mathbf{V}_i}{dt} = m_i \mathbf{g} + \frac{1}{2} \rho_a C_D ||\mathbf{v}_s \mathbf{v}_i|| (\mathbf{v}_s \mathbf{v}_i) A_i$
- THERMO: $m_i C_i \frac{d\theta_i}{dt} = hA_i^s(\theta_s \theta_i) + \epsilon \beta A_i^s(\theta_s^4 \theta_i^4) + \gamma \frac{1}{2} \rho_a C_D ||\mathbf{v}_s \mathbf{v}_i||^3 A_i$

MANUFACTURING SAFETY: SPATIO-TEMPORAL FOOTPRINTS OF INCANDESCENT EJECTA









- Zohdi, T. I. and Wriggers, P. (Book, 2008) Introduction to computational micromechanics. Second Reprinting. Springer-Verlag.
- Zohdi, T. I. (Book, 2012) Electromagnetic properties of multiphase dielectrics. A primer on modeling, theory and computation. Springer-Verlag.
- Zohdi, T. I. (Book, 2017). Modeling and simulation of functionalized materials for additive manufacturing and 3D printing: continuous and discrete media. Springer-Verlag.
- POSTED PAPERS: http://www.me.berkeley.edu/faculty/zohdi/